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SECTION A.—MATHEMATICAL AND PHYSICAL SCIENCES.

β -Ray Spectra and their Meaning.

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Introduction.

In a previous paper,* I described some measurements of the magnetic spectrum of the β -rays ejected from various metals by the γ -rays of radium B. These experiments showed that the conversion of monochromatic γ -rays into β -rays was described by the same quantum relation that holds for X-rays and light, and using this knowledge it was found possible to give a complete explanation of the natural β -ray spectrum of radium B. Sir Ernest Rutherford† had already shown that the lines in the β -ray spectrum were due in some way to the conversion of monochromatic γ -rays in the same radio-active atom that emitted them, and these experiments on the excited spectra now proved that the strong lines were due to the conversion of the γ -rays in the K ring, and the weaker lines to conversion in the L_3 ring.

This explanation of the line β -ray spectrum is, by itself, of considerable interest, but of far greater importance is the fact that these experiments give a method of finding the wave-lengths of γ -rays. The shortest wave-length that has been measured by the crystal method is $0\cdot07 \text{ \AA.U.}$,‡ and at present it seems almost impossible to extend this range much further by this method. Since many radio-active bodies emit γ -rays of shorter wave-length than this any method by which these wave-lengths may be found is important.

The method is as follows: The first step is to measure the energies of the different lines in the natural β -ray spectrum of the body. If a certain line

* Ellis, 'Roy. Soc. Proc.,' A, vol. 99, p. 261 (1921).

† Rutherford, Robinson and Rawlinson, 'Phil. Mag.,' vol. 28, p. 281 (1914); Rutherford 'Phil. Mag.,' vol. 34, p. 153 (1917).

‡ Rutherford and Andrade, 'Phil. Mag.,' vol. 28, p. 263 (1914).

corresponds to an energy E_1 , and is produced by the conversion of a γ -ray of frequency ν

$$E_1 = h\nu - w_1,^*$$

where w_1 represents the work to remove the electron from its position inside the atom to the surface. To find the frequency of the γ -ray all that is necessary is to determine the quantity w_1 . This may be done by measuring the energy of the corresponding line in the excited spectra of a body of neighbouring atomic number. In this second case the electron will come from the corresponding level, but the work done in removing it to the surface of the atom will be different w_2 . The difference in the energies of the two corresponding β -ray lines $E_2 - E_1$ is clearly equal to $w_1 - w_2$, and is determined directly. To find w_1 , all that is necessary is to see which of the corresponding levels of the two atoms differ by this amount. This can be done from the X-ray absorption data, which also gives the absolute magnitude of w_1 .

Where this method can be applied it leads to perfectly definite results, but it is not always possible to obtain sufficiently strong sources to enable excited spectra to be measured. In this case the natural β -ray spectrum has to be analysed by inspection. Very frequently two or more lines can be found which differ in energy by the same amount as certain known levels in the atom, for instance, the K and the L levels, or the $L_3L_2L_1$ levels. It is then reasonably certain that the β -ray lines in question originate in these levels by the action of the same γ -ray.

The γ -rays of radium B, radium C, and thorium D have been investigated by these methods, and the measurements are given in the following sections. There is considerable evidence that these γ -rays come from the nucleus and are characteristic of its structure, and it is already possible from these measurements to obtain some information about this structure. This is of special interest since, at the moment, there seems to be no other method of attacking the problem of the structure of the heavy nuclei.

The γ -Rays of Radium B.

The complete β -ray spectrum of radium B, as measured by Rutherford and Robinson,[†] is shown in the next Table.

The first eleven lines were analysed by the excited spectrum method, and the results were given in the paper already referred to.[‡] These lines

* The experiments described on pp. 264 and 265 of the previous paper have been extended to include Ag (At. No. 47). The values of the γ -ray energies deduced are 2.92 and 3.48×10^6 volts. This gives a sufficient range of atomic number to show that the equation $E = h\nu - w$ is exact.

† Rutherford and Robinson, 'Phil. Mag.', vol. 26, p. 717 (1913).

‡ Ellis, *loc. cit.*

are due to six γ -rays of wave-length of the order of $0.04 \text{ \AA.U.}$, ejecting electrons from the K and L_3 levels of the radium B atom. The diffuse groups 12 and 13 have now also been analysed by the same method, using the same experimental arrangement.

Table I.—Groups of β -Rays from RaB.
(Measured by Rutherford and Robinson.)

No.	Energy of group in volts.	No.	Energy of group in volts.
1	3.851×10^5	9	2.031×10^5
2	3.473	10	1.645
3	3.328	11	1.494
4	3.103	12	0.743-0.694
5	2.756	13	0.618-0.585
6	2.608	14	0.535
7	2.364	15	0.500
8	2.227	16	0.375

Two corresponding groups of slightly greater energy were observed in the excited β -ray spectrum of platinum, and the increase of energy agreed with the difference in energy between the L levels of lead and platinum, showing that these groups are due to the conversion of γ -rays in the L ring. The γ -rays in question are the "K" X-radiations of radium B, the first group being due to K_β and K_γ , and the second group to K_α . This may be seen from Table II.

The agreement is fair, but not very good, and another point is that this Table indicates a series of lines and not the diffuse groups actually observed. The same causes probably explain both facts. Radium C emits β -rays in this region,* which almost certainly have the same origin, but the energies will be slightly greater. Again, it must be remembered that the groups are due to the ejection of an electron from the L ring of an atom by the radiation emitted by an electron returning to the K ring of the same atom, and returning either from or through this L ring. Under these circumstances it is unlikely that calculations based on the normal L levels can be very accurate.

The origin of the remaining prominent β -ray lines numbered 14, 15, and 16 has not been determined. Several attempts were made to measure the corresponding lines in lead and platinum, but no satisfactory results were obtained. The experimental method is not suitable for these low velocities, and it was not anticipated that excited lines corresponding to the less prominent lines 14 and 15 would be obtained, but No. 16 is a very strong one and should have yielded results. This line in the natural spectrum

* Rutherford and Robinson, *loc. cit.*, p. 727.

Table II.—Showing Origin of β -Ray Groups 12 and 13 of Table I.

RaB K lines.		RaB L levels.†	
λ in Å.U.	Energy in volts.	λ in Å.U.	Energy in volts.
K α ... 0·169	0·731 $\times 10^5$ *	L ₁ ... 0·9487	0·130 $\times 10^5$
K β ... 0·149	0·829†	L ₂ ... 0·8128	0·152
K γ ... 0·143	0·864†	L ₃ ... 0·7808	0·158

Origin of group.	Energy of group in volts. (Calculated.)	Energy of group. (Observed.)	
K α —L ₃	0·573 $\times 10^5$	}	0·585 $\times 10^5$
K α —L ₂	0·579		to
K α —L ₁	0·601		0·618
K β —L ₃	0·671	}	
K β —L ₂	0·677		
K β —L ₁	0·699		0·694
K γ —L ₃	0·706		to
K γ —L ₂	0·712		0·743
K γ —L ₁	0·734		

* Ledoux-Lebard and Dauvillier, 'Physique des Rayons,' X, p. 75.

† Ledoux-Lebard, *loc. cit.* (extrapolated).‡ Ledoux-Lebard, *loc. cit.*, p. 69.

appears to be almost a narrow band, and it is possible that it is composed of β -rays of different origins. For instance, the γ -ray of wave-length 0·099 Å.U., measured by the crystal method by Rutherford and Andrade, would eject an electron of this energy from the K ring, and again, the γ -ray 0·229 Å.U. acting on the L₃ ring would fit the results, and the same γ -ray acting on the M and exterior rings might give lines 15 and 16. Some evidence on these possibilities has been obtained from excited spectra, but it would require a large amount of work to complete the analysis.* The general evidence indicates that the β -ray emission in this region is due to the γ -rays measured by Rutherford and Andrade by the crystal method, and since the wave-lengths had been determined accurately already, it was not thought necessary to carry the β -ray method any further.

The γ -ray spectrum of radium B extends without any appreciable gaps from 0·03 Å.U. to the L X-ray region, about 1·3 Å.U., and the wave-lengths of all the main lines are now known.

* Some recent experiments suggest strongly that this group is due to the γ -ray $\lambda = 0·229$ Å.U., as described in the text.

The γ-Rays of Radium C.

The β -ray spectrum of radium C has been measured by Rutherford and Robinson,* and their results are shown in the next Table. This only includes the lines up to energy 5.94×10^5 volts; the lines of greater energy will be treated in a subsequent paper.

Table III.—The β -Ray Groups of RaC.
(Measured by Rutherford and Robinson.)

No.	Intensity.	Energy in volts.
H	m.s.	5.94×10^5
36	m.f.	5.67
37	m.f.	5.44
K	s.	5.15
39	f.	4.91
40	f.	4.79
41	m.f.	4.48
42	f.	4.05
43	f.	3.33
L	m.	2.96
M	m.	2.59
N	m.	1.81
47	f.	1.59
48	f.	1.49

These β -rays have been investigated by the excited spectrum method.

The line corresponding to K in Table III was observed excited in platinum and uranium, and the results are shown in the next Table.

Table IV.

Metal.	Atomic number.	Energies in volts.
Platinum	78	5.28×10^5
Radium C.....	83	5.15
Uranium	92	4.86

It is seen that there is a large shift, which suggests the K ring as the origin of the line. This is proved by adding to each of the above values the corresponding K absorption energy, respectively

0.78 0.92 1.18×10^5 volts,

when the following values are obtained for the γ -rays energy,

6.06 6.07 6.04×10^5 volts.

The agreement is thus very good.

* Rutherford and Robinson, *loc. cit.*

The line H is certainly the result of this same γ -ray ejecting electrons from the L_3 ring. For in this case the energy would be

$$\gamma\text{-ray energy minus } L_3 \text{ absorption energy.}$$

For radium C this would give

$$(6\cdot07 - 0\cdot16) \times 10^5 = 5\cdot91 \times 10^5,$$

and Rutherford's measurement is $5\cdot94 \times 10^5$.

It was found possible to make approximate measurements of the corresponding line from uranium,

$$\text{Calculated..... } (6\cdot07 - 0\cdot22) \times 10^5 = 5\cdot85 \times 10^5,$$

$$\text{Measured } 5\cdot91 \times 10^5.$$

There is, therefore, conclusive evidence that radium C emits a γ -ray of characteristic energy,

$$6\cdot07 \times 10^5 \text{ volts,} \quad \text{wave-length } 0\cdot0203 \text{ \AA.U.}$$

It is extremely probable that the remaining lines in the β -ray spectrum are the result of five or more weaker γ -rays ejecting electrons from the K and L_3 rings, but the γ -rays are not sufficiently intense for measurements of the excited spectra to be possible. A certain amount, however, can be deduced by inspection. There are three pairs of lines 36 and 39, 40 and 42, and M and N showing a constant difference of energy equal to the difference of the K and L_3 absorption energies of radium C, that is $0\cdot76 \times 10^5$ volts. This indicates that these six lines are due to the conversion in the K and L_3 rings of three γ -rays, and the characteristic energies of these γ -rays are obtained by adding to the energies of the β -ray lines the K absorption energy $0\cdot92 \times 10^5$ volts and the L_3 absorption energy $0\cdot16 \times 10^5$ volts respectively.

The γ -rays of radium C which have been found are collected in the next Table. This list includes all the prominent γ -rays of wave-length greater than $0\cdot02 \text{ \AA.U.}$ with the exception of the one giving the line L. It seems very likely that this line is due to the conversion in the K ring of a γ -ray of energy $3\cdot88 \times 10^5$ volts and wave-length $0\cdot0318 \text{ \AA.U.}$, but since this is not certain it is not included in the Table.

Table V.— γ -Rays of RaC. (Deduced from the β -Ray Spectrum.)

Intensity.	Energy in volts.	λ in $\text{\AA.U.}$
m.	$2\cdot74 \times 10^5$	0·0450
f.	4·96	0·0249
f.	5·83	0·0212
s.	6·07	0·0203

The β -Rays of ThC and D.

The measurements of the β -ray spectrum were made by the original method of Rutherford and Robinson,* using as source a small nickel plate 3 mm. by 10 mm. with the active material deposited on it. This has several advantages over the usual thin wire. It is easier to prepare, it can easily be arranged that all the active material is on one side so that it is all effective, and lastly the area of such a source is relatively large and, with a given quantity of radioactive substance from which the active material is to be obtained, the amount deposited is approximately proportional to the area.

Table VI.—Groups of β -Rays from ThC+D. (Measured by Ellis.)

Number.	Intensity.	Energy in volts. (Observed.)	Origin.	γ -ray.	Energy in volts. (Calculated.)
1	f.	8.02×10^5			
2 A	m.s.	7.74			
3	m.f.	6.96			
4 B	m.s.	6.37	L_3	1	6.39
5 C	m.s.	5.68	K	1	5.67
6	m.f.	5.35			
7	m.f.	5.09			
8 D	v.s.	4.97	L_3	2	4.96
9 E	v.s.	4.24	K	2	4.24
10	f.	3.88			
11	f.	3.47			
12 F	m.s.	2.71	L_3	3	2.71
13 G	m.s.	2.59	L_3	4	2.59
14	m.f.	2.44			
15	m.	2.395	L_3	5	2.39
16	f.	2.32	L_3	6	2.33
17	m.f.	2.12	L_3	7	2.13
18 H	s.	1.992	K	3	1.99
19	m.f.	1.908	L_3	8	1.91
20 K	v.s.	1.869	K	4	1.87
21	m.	1.665	K	5	1.67
22 L	m.s.	1.614	K	6	1.61
23	f.	1.505			
24 M	m.s.	1.421	K	7	1.41
25	f.	1.247			
26 N	m.s.	1.197	K	8	1.19
27	m.	1.040			
28	f.	0.880			
29	f.	0.743			
30	f.	0.563			
31	m.	0.412	L_2	9	0.413
32	s.	0.406	L_3	9	0.406
33	m.	0.387	M_1	10	0.384
34 O	v.s.	0.375	M_3	10	0.377
35	m.	0.280	L_1	10	0.281
36	s.	0.261	L_2	10	0.261
37 P	v.s.	0.254	L_3	10	0.254

A source of this size, if used in the ordinary way, would give very poor focussing, but this can be avoided by tipping it towards the

* Rutherford and Robinson, *loc. cit.*

photographic plate so that the effective β -rays come off at nearly grazing incidence.

Sources of thorium C and D were obtained by immersing the nickel plate in a hot acid solution of radiothorium for about half an hour. The average source was 2 to 3 mgrm. The purity was always verified by measuring the decay. Since both thorium C and thorium D emit β -particles and both were present on the active sources it is impossible to tell to which body the β -ray lines belong. This point is treated in detail later.

The β -ray emission has been investigated from 2.0×10^4 volts to 1.9×10^6 volts. Over the whole of this range there is a background of continuous β -ray emission with a maximum of photographic effect about 2.0×10^5 volts. A great many β -ray lines have also been measured and the results are shown in the first three columns of the next Table. The last seven lines were given in the previous paper but are repeated here for completeness. There was an error in the calculation of line 33 which is now corrected. All these measurements refer to Rutherford and Robinson's* determination of the β -rays of radium B as standard.

Hahn† found a broad band in the region 8.70 to 11.2×10^5 volts, but in the present experiments no lines were found above 8.0×10^5 volts.

The γ -rays of ThD.

Sufficiently strong sources of thorium C and D cannot be obtained to make the measurement of excited spectra practicable, so the deduction of the γ -rays from the β -ray spectrum has to be done by inspection. From analogy with radium B and C it is to be expected that the β -rays in the region 1.2 to 6.0×10^5 volts will be due to conversion of γ -rays in the K and the L_3 rings. If this is so it should be possible to group the lines in pairs, the energy difference between the members of a pair being equal to the K absorption energy minus the L_3 absorption energy, and the line due to conversion in the K ring should be the stronger one of the pair.

There is another difficulty, however, because it is not known whether these lines are to be ascribed to thorium C (atomic number 83) or to thorium D (atomic number 81). Many attempts were made to take β -ray photographs with a pure source of thorium D prepared by recoil, but no definite results were obtained. Large sources of active material would be necessary in order to settle this question, and the whole problem is made more difficult by the short period of thorium D (3.1 minutes).

Measurements on the absorption of the γ -radiation emitted by thorium C

* Rutherford and Robinson, *loc. cit.*

† Hahn, 'Phys. Zeit.,' vol. 12, p. 273 (1911).

and thorium D, throw some light on this point. Thorium C emits γ -rays only in small quantities, and the main γ -radiation of thorium C + D is to be ascribed to thorium D*, which would suggest that these β -ray lines are certainly not due to thorium C and so presumably come from thorium D. Against this is to be noted that nearly all of the γ -radiation from thorium D is of one very hard type,[†] and no evidence was obtained of softer γ -rays or of the characteristic K and L radiations which would result from the ejection of electrons from the K and L rings. This may not be a very serious objection since at first similar results were found for radium C, and it was only later that Richardson[‡] detected softer γ -rays and the K radiations.

The internal evidence from the β -ray lines suggests strongly that they come from thorium D (atomic number 81), since all of the strong lines can be coupled in pairs, having a difference of energy 0.72×10^5 volts equal to the difference in energy of the K and L absorptions of a body of atomic number 81. Compared to the eight pairs found in this way only two pairs can be found to agree with thorium C (atomic number 83) corresponding to a separation of 0.76×10^5 volts.

The agreement that is obtained if these lines be assigned to thorium D may be seen from the last three columns of Table VI. The fourth column shows the origin of the line, the fifth column shows which of the γ -rays given in Table VII produces the line, and the last column gives the calculated energies.

On these grounds it will be assumed provisionally that these lines are due to thorium D, and the same assumption will be made about the last seven lines, due to conversion in the L rings, although neither the absorption measurements nor the β -ray evidence throw any light on the origin of this group.

These seven lines may be due to three γ -rays of characteristic energies 0.408, 0.531, 0.540×10^5 volts, ejecting electrons from the L rings. This view was put forward in the previous paper. It is also possible that they are produced by only two γ -rays, the first one (No. 10) ejecting electrons from the M ring as well. The agreement obtained on this hypothesis can be seen from Tables VI and VII. Approximate values for the M absorption voltages were obtained by interpolation ($M_1 = 0.024 \times 10^5$, $M_3 = 0.031 \times 10^5$).§

* Rutherford and Richardson, 'Phil. Mag.,' (2), p. 937 (1913); Meitner and Hahn, 'Phys. Zeit.,' vol. 14, p. 873 (1913).

† Rutherford and Richardson, *loc. cit.*

‡ Richardson, 'Roy. Soc. Proc.,' A, vol. 91, p. 396 (1915).

§ Coster, 'Zeit. f. Physik,' [5], p. 139 (1921).

It is not possible to settle definitely which of these explanations is correct, but the results obtained from some recent experiments support the view given in this paper.

The γ -rays of thorium D are shown in the next Table. The absorption voltages used are also given.

Table VII.— γ -Rays of ThD. (Deduced from the β -Ray Spectrum.)

Number.	Energy in volts.	λ in Å.U.
1	6.54×10^5	0.0189
2	5.11	0.0241
3	2.86	0.0431
4	2.74	0.0450
5	2.54	0.0486
6	2.48	0.0498
7	2.28	0.0541
8	2.06	0.0599
9	0.560	0.220
10	0.408	0.302

Absorption Voltages ThD. (At. No. 81.)

Ring.	Energy in volts.	λ in Å.U.
K	0.869×10^5	0.1427*
L ₃	0.154	0.803†
L ₂	0.147	0.840†
L ₁	0.127	0.974†

* Siegbahn and Jönsson, 'Phys. Zeit.,' vol. 20, p. 252 (1919).

† Ledoux-Lebard and Dauvillier, 'Physique des Rayons X,' p. 69.

Discussion.

The monochromatic γ -rays emitted by several radioactive bodies have been investigated by the β -ray method, and it is of interest to compare these results with those obtained by absorption measurements. The absorption method can only effect a rough analysis of the total γ -ray emission into several types, each type being absorbed according to a simple exponential law. This analysis cannot be very detailed, and it would be impossible to differentiate between a single line and the number of lines grouped around one of greater intensity.

The γ -rays of radium B have been investigated most completely, and it is best to make the comparison between the two methods for this body.

The total γ -ray spectrum of radium B is shown in the next Table. The first column contains the γ -rays of radium B and C as measured by Rutherford

and Andrade,* by the crystal method ; the second column the γ -rays measured by the writer, by the β -ray method. All of those in the second column come from radium B, whereas those in the first column are an unresolved mixture, some coming from radium B and some from radium C. In addition, Rutherford and Andrade measured the complete L and K spectra which are excited by the γ -rays, these are summarised under the heads L and K groups. The μ/ρ of the different types of radiation detected by Rutherford and Richardson† are given in the following Table :—

Table VIII.—The γ -Rays of RaB and C.

RaB and C. (Measured by Crystal, Rutherford and Andrade.)		RaB. (Deduced from the β -Ray Spectrum, Ellis.)	
λ in A.U.	Intensity.	λ in Å.U.	Energy in volts.
L spect. RaB	v.s.	0·0519	$2\cdot385 \times 10^5$
L spect. RaC	m.s.	0·0488	2·529
1·365	} —“ a ”	0·0423	2·918
1·286		v.s.	3·492
1·266		v.s.	3·639
1·219		m.s.	4·000
1·074		f.	
1·029	} —“ b ”		
0·853			
0·428			
0·324			
0·262	} —“ c ”		
0·229			
K spect. RaB			
K spect. RaC			
0·115			
0·099			
0·071			

Table IX.— μ/ρ of the γ -Rays of RaB and C.
(Determined by Rutherford and Richardson.)

RaB and C.		RaB.	
μ/ρ Al.		μ/ρ Pb.	
85		4·0	
14·7		0·53	
0·188		0·13	

* Rutherford and Andrade, ‘Phil. Mag.’ (1), p. 869 (1914), and (2), p. 263 (1914).

† Rutherford and Richardson, ‘Phil. Mag.’ (1), p. 722 (1913) ; Richardson, ‘Roy. Soc. Proc.,’ A, vol. 91, p. 396 (1915).

The value μ/ρ in Al = 85 corresponds to very soft X-rays, possibly M characteristic radiations.

The L radiations of bodies of atomic number 82 and 83 have μ/ρ of 17.4 and 16.1 respectively, and so the value found, 14.7, almost certainly represents the combined L radiations of radium B and C, hardened by the superposition of the much less intense group labelled "b"; the group "a" being in the region of the L spectrum would have no effect.

The characteristic K radiations of bodies of atomic numbers 82 and 83 have μ/ρ in Al 0.192 and 0.178 respectively, and in Pb about 4. It can be seen from the Table that values very close to these were found, indicating that the three γ -rays forming group "c" have relatively little energy associated with them.

As Sir Ernest Rutherford* has already pointed out, the two groups found by Richardson for radium B having μ/ρ in Pb 0.53 and 0.13 correspond approximately to the γ -rays in the second column of Table IX.

The chief conclusions that may be drawn from this comparison are as follows. Absorption coefficients in aluminium of value greater than about 0.16 are determined mainly by the characteristic X-rays which are excited by the γ -rays. Departures of these values from those of an ordinary element of the same atomic number as the radio-active element indicate the presence of extra radiations not included in the ordinary X-ray spectrum and characteristic of the radio-active element. For instance, Rutherford and Richardson† found two groups for thorium B (atomic number 82) for which μ/ρ in Al had values 11.8 and 0.13. Since the K and L radiations alone would give 17.4 and 0.19 there are evidently relatively strong extra radiations of the type labelled "b" and "c" in the radium B γ -rays. It is important to note that the presence of the characteristic K radiations shows the existence of higher frequency γ -rays which eject electrons from the K ring. Hence thorium B and also actinium B with a μ/ρ in Al of 0.165 must emit γ -rays analogous to the main γ -rays of radium B. Such γ -rays could be detected directly by absorption measurements such as Richardson carried out for radium B.

Radium C and thorium D emit a very hard type of radiation having μ/ρ in Al of the order 0.025. The occurrence of β -ray lines of very high energy shows that radium C emits monochromatic γ -rays corresponding to 1—3 million volts in considerable intensity, and these γ -rays probably form part of the hard type of radiation, but it is unlikely that they form all of it since thorium D which emits a slightly harder type of radiation appears to emit no monochromatic γ -rays of energy greater than 800,000 volts. It was

* Rutherford, 'Phil. Mag.', vol. 34, p. 153 (1917).

† Rutherford and Richardson, 'Phil. Mag.', vol. 26, p. 937 (1913).

pointed out, however, that thorium D does emit a general distribution of β -rays which extends to very high energies, so the hard type of radiation emitted by thorium D may be "white" γ -radiation of high average frequency emitted as a result of the retardations of these β -particles in their escape from the nucleus. Very little, therefore, at present can be deduced from the detection by absorption measurements of a hard type of radiation. The general results suggest that such a hard type may be either monochromatic γ -rays or "white" γ -rays of high average frequency, or a mixture of these.

Relation of the Characteristic γ -Rays to the Structure of the Atom.

The wave-lengths of these γ -rays depend on the structure of that part of the atom which emits them, and considerable information about this structure can be deduced from the experimental results.

The first point is to settle the origin of the γ -rays. Sir Ernest Rutherford has pointed out on several occasions that the general results indicate that γ -rays are emitted from the nuclei of radio-active atoms, and the numerical values now obtained lend very strong support to this view.

Except as regards the constitution of the nucleus, the radium B atom is identical with the lead atom in every respect. In particular, the K and the L rings, and the fields of force in which they are situated, must be precisely the same in the two atoms, since Rutherford and Andrade found that radium B emits the complete K and L spectrum of a body of atomic number 82. But this last fact indicates something more than this, it suggests that the γ -rays are emitted previous to the actual disintegration of the radium B nucleus, that is to say, previous to the emission from the nucleus of the disintegration electron resulting in the atomic number changing to 83. In fact, it would appear that the γ -ray is emitted, travels out to the L ring, from where it may eject an electron, this electron goes clear of the atom and another electron falls into the vacant place in the L ring, and the nucleus has still not disintegrated.

The main γ -rays of radium B correspond to energies $2.4-4.0 \times 10^5$ volts. If they owe their origin to a transition between stationary states in the electronic system of the atom, the end state must be very deep in the atom and certainly inside the K ring, but this possibility is ruled out completely by some work of Chadwick.* He investigated the field of force between the nucleus and the K ring of heavy atoms by observing the deflection of α -particles passing through this region, and he shows that no electrons are present there. Since radium B is identical with lead, except as regards the constitution of the nucleus, this must also apply to radium B. It seems almost certain, therefore, that these γ -rays must come from the nucleus, and

* Chadwick, 'Phil. Mag.', vol. 40, p. 734 (1920).

since they are emitted previous to the actual disintegration it should be possible to deduce information about the normal radium B nucleus from them.

The main γ -rays of radium B, with their energies, were given in the right-hand column of Table IX. There is a simple arithmetical connection between these energies, the first three being respectively about $1\cdot10 \times 10^5$ volts greater than the last three. If the quantum dynamics holds in the nucleus this arithmetical connection would mean that there were five levels, transition between these levels resulting in the emission of the γ -rays. These levels are shown in fig. 1, with arrows indicating the origin of the γ -rays.

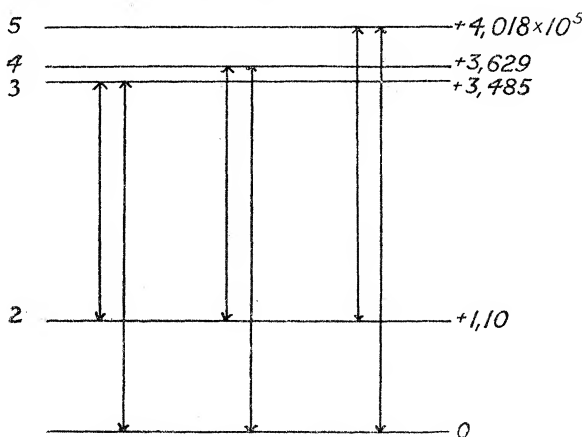


FIG. 1.

But as a necessary consequence of the existence of these levels, there should also be γ -rays corresponding to transitions 5 to 4, 5 to 3, 4 to 3, and 2 to 1. γ -rays corresponding to these energy differences were actually measured by Rutherford and Andrade, by the crystal method, in their work on the γ -rays of radium B and C (see Table IX), and the agreement between the observed and calculated values may be seen from the next Table.

Table X.

Origin.	Energy in volts.	λ in Å.U. (Calculated.)	λ in Å.U. (Observed.)
5-4	$0\cdot389 \times 10^5$	0·318	0·324
5-3	0·533	0·231	0·229
4-3	0·144	0·857	0·853
2-1	1·10	0·112	0·115

The agreement is good and lends support to the view that quantum dynamics apply to the nucleus, and that part at least of the structure of the nucleus can be expressed in terms of stationary states.

If this result be confirmed, it will be of great importance in elucidating the structure of the nucleus, but it would be premature to consider its general bearing at the moment.

The information that has been deduced from these characteristic γ -rays is peculiar in two respects. When it is considered how little is known about the nuclei of heavy atoms, the information that is contained in fig. 1 about the energies of the stationary states of the radium B nucleus is extraordinarily detailed, but, on the other hand, this information is very limited. There is no evidence which indicates whether these levels are occupied by positively charged particles or by electrons, nor is it possible to associate level 5 or level 1 with any special part of the nucleus.

Sir Ernest Rutherford has shown that the emission of the γ -rays is directly connected with the disintegration, but it is very difficult to settle which is the primary phenomenon. This point has been already mentioned in this paper, but it is important to consider the evidence in more detail, since, if the order were reversed, the levels shown in fig. 1 would probably refer to some system other than the radium B nucleus.

The only argument that can be used depends on the fact that the L spectrum emitted by radium B agrees so well, both as regards wave-length and intensity, with that of lead that it is certain that the L, M, N, ... rings are still identical at the moment of emission with those of a body of atomic number 82. It cannot be asserted definitely, however, that at that same moment the nuclear charge is still 82 units. So little is known about the processes involved in the transition from one stationary state to another that it is possible that there may be a time of relaxation, so that the L, M, N, ... rings of the 82 body may persist for a certain time after the nuclear charge has become 83. If this time of relaxation is greater than the interval between the emission of the γ -ray and the emission of the L spectrum then it is clear that the experimental results are consistent with the hypothesis that the disintegration occurs before the emission of the γ -ray. If, on the other hand, it be assumed that the emission of the γ -ray precedes the disintegration, there is no need to make any hypothesis about the existence of a time of relaxation.

There does not appear to be any more evidence which bears on the question at all,* and so, since the view that the γ -ray comes first is at least *a priori* of

* It should be noted that on both these views the rate of decay measured by β -rays or γ -rays will be identical provided the average time before the first phenomenon is long compared to the average time between the first and second. The average time before the first phenomenon is the ordinary period, and the general results suggest that either view would fulfil this condition.

equal probability as the opposite view, and since, in addition, it does not involve any extra hypothesis about a time of relaxation, it will be assumed provisionally to be true.

There are several consequences that result from this decision. Firstly, the levels shown in fig. 1 can be assigned to radium B, and they are considered to represent the normal structure of the nucleus. Secondly, the general picture of a β -ray transformation is different from that which one would make if the disintegration were to occur first. This last case has already been treated by Sir Ernest Rutherford; the result of the alternative view may be illustrated by considering the radium B transformation.

The radium B nucleus comes into existence after the α -particle has left the radium A nucleus, but one would not anticipate that all the radium B nuclei were absolutely identical. The particle which does the transitions between the levels of fig. 1 will be in one of these levels, but it need not be in the same level in each nucleus. Subsequently, during the life of the nucleus this particle passes to another energy level with the emission of a γ -ray. Finally, the particle will arrive in one of the states which is connected with instability, and the nucleus disintegrates with emission of an electron.

This view suggests a clear distinction between the γ -ray and the β -ray lines, on the one hand, and the continuous β -ray spectrum, on the other. The former are characteristic of the normal life of the nucleus and give information about its structure. The latter is characteristic of the disintegration of the transition of one element to another and is analogous to the α -rays.

An interesting point arises from the consideration of energy levels in the nucleus. In Table VIII, showing the γ -rays of radium B and C, there are two groups labelled "b" and "c," whose wave-lengths do not coincide at all with either the K or the L spectra, yet the wave-lengths are of a magnitude that, in the absence of other evidence, would indicate their origin to be somewhere in the electronic structure of the atom, whereas all X-ray evidence goes to prove that there are no other states besides the K, L, M, etc. Four of these lines have been accounted for in the above Table, and it is reasonable to suppose that the remainder originate in the same way, in either the radium B or radium C nucleus.

Too few γ -rays of radium C have been identified for it to be possible to obtain independent evidence about the existence of nuclear levels, but it is interesting to note that if the γ -rays that have been measured are fitted into a set of levels, this set would also give γ -rays which, on conversion in the K ring of radium C, would give β -ray groups agreeing with Rutherford's measurements.

The measurements of the γ -rays of thorium D, however, are sufficiently detailed to give strong confirmation of the hypothesis about stationary states in the nucleus. A set of eight stationary states is postulated, consisting of four groups, the energies being 0.41 and 0.56×10^5 volts, 2.28 , 2.48 , 2.54 , 2.74×10^5 volts, 5.11×10^5 volts, and 9.02×10^5 volts. This set of levels gives the ten γ -rays actually measured, and in addition gives eight more γ -rays which, on conversion in the K ring of thorium D, would produce β -ray groups agreeing with those measured. This result may be stated another way by remarking that this set of levels would give γ -rays which would account for thirty-three out of the thirty-seven β -ray groups actually measured.

The general results lend strong support to the view that stationary states exist in the nucleus, and it is hoped that by investigating the γ -rays of other radio-active bodies, some general principles in the arrangement of nuclear levels may be found.

Summary.

1. A general method for measuring the wave-length of γ -rays is given.
2. The analysis of the β -ray emission of radium B has been completed.
3. The lower energy section of the radium C β -ray spectrum has been analysed by the excited spectrum method and the γ -rays found.
4. The β -ray spectrum of thorium D has been measured and the effective γ -rays deduced.
5. It is shown that it is very probable that the γ -rays of radio-active bodies are emitted from the nucleus.
6. Evidence is brought to show that the quantum dynamics applies to the nucleus, and suggestions for the arrangement of the nuclear levels of radium B and thorium D are given.

In conclusion, I should like to express my indebtedness to Prof. Sir Ernest Rutherford for his constant help and direction. My thanks are due to Mr. G. R. Crowe for the preparation of the active sources used.